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Description

Method and device for polarizing a piezoelectric actuator

The invention relates to a method for polarizing a piezoelectric actuator in accordance with the preamble of claim 1 and to a device for polarizing a piezoelectric actuator in accordance with the preamble of claim 9.

Piezoelectric actuators are employed in a wide variety of technical fields to actuate control elements. In such applications the piezoelectric actuators have the significant advantage of making possible rapid actuation with high dynamics and a high force.

A piezoelectric actuator is constructed from a plurality of piezoelectric layers. The individual piezoelectric layers are each arranged between two metal electrodes. To actuate the piezoelectric actuator an electrical voltage is applied to the piezoelectric layers, leading to a lengthening of the individual piezoelectric layers and to a lengthening of the piezoelectric actuator as a whole. So that the piezoelectric layer has a piezoelectric effect after it has been manufactured, whereby the thickness of the piezoelectric changes on application of an electrical voltage, it is necessary to first polarize the piezoelectric layers.

To polarize the piezoelectric layers an electrical polarization field, i.e. an electrical voltage is applied, which produces a remanent polarization and an ordered distribution of the domains aligned into the piezoelectric layers in the field direction of the polarization field

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compared to the unpolarized initial state. After the polarization of the piezoelectric layers the piezoelectric layers are remanent, i.e. permanently lengthened in the direction of the applied polarization field. The remanent lengthening of the piezoelectric layers is tailored to the stress conditions during the use of the piezoelectric actuator in that the polarization is undertaken under compressive stress. This reduces settling effects of the piezoelectric layers, which occur after polarization. A corresponding generic method is known from the International Patent Application with the international publication number 99/31739.

For polarizing the piezoelectric actuator voltages which can be changed over time are used since this achieves an improved polarization. The length of the piezoelectric actuator changes during the polarization process in accordance with the voltage pulses applied. Since the piezoelectric actuator is tensioned between two holders to represent the compressive stress, the compressive stress exerted by the holders on the piezoelectric actuator is changed by the change in length of the piezoelectric actuator. This has a negative effect on the polarization process of the piezoelectric actuator.

The object of the invention is to provide a method and a device for polarizing a piezoelectric actuator with which an improvement of the polarization process is possible.

The object of the invention is achieved by the method in accordance with claim 1 and by the device in accordance with claim 9.

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Further advantageous embodiments of the invention are specified in the dependent claims.

One advantage of the invention is that the pre-stressing force during the polarization is essentially kept constant. To this end a second piezoelectric actuator is arranged between the first piezoelectric actuator and the pretensioning retaining element which equalizes the length on polarization of the first piezoelectric actuator. This ensures that the total length of the two piezoelectric actuators essentially remains constant. Thus the position of the retaining elements of the pretensioning holder can essentially be kept constant after a start phase.

The second piezoelectric actuator is in this case supplied with a changing voltage with a phase offset to the first piezoelectric actuator, in which case after a start phase in which the amplitude of the voltages is increased the two voltages are defined in a manner in which the sum of the voltages remains approximately constant. The result of this is that the total length of the two piezoelectric actuators essentially remains constant during the polarization process. This makes it possible to define a constant pretensioning force at the beginning of the polarization process on the two piezoelectric actuators by adjusting the position of the retaining elements of the pretensioning holder without it being necessary to have to change the position of the retaining elements of the pretensioning holder after the start phase during the polarization of the first and/or the second actuator.

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Because of the inventive method it is possible to apply the voltages which are used for polarization of the piezoelectric actuators with a high-frequency. Since the piezoelectric actuators exhibit a high dynamic during the changes in length it is possible to compensate for the rapid changes in length of the first piezoelectric actuator by a correspondingly rapid change in length of the second piezoelectric actuator. Correspondingly high-frequencies could not be achieved by changing the position of the retaining elements since their kinetic energy does not allow a corresponding dynamic movement.

Preferably the voltages which are simultaneously applied to the two actuators are defined in a manner in which the increase or reduction of the voltage at the electrodes of the first actuator is equal to the reduction or the increase of the voltage at the electrodes of the second actuator. In this manner the voltage changes operating on the piezoelectric layers of the two actuators are selected to be equal in size.

In a further embodiment of the inventive method the change in length of the first and/or the second piezoelectric actuator during a start phase is compensated for by a positional change of the retaining elements of the pretensioning holder during the polarization process. Also in this manner the compressive stress which operates on the piezoelectric actuators during the polarization process is kept approximately constant despite the change in length.

The inventive device has the advantage that during a polarization process of a first piezoelectric actuator high

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dynamic changes in length which occur can be compensated for precisely by a second piezoelectric actuator so that the pretensioning force operating during the polarization process on the first and/or the second piezoelectric actuator is essentially kept constant. To this end the device features a control unit which undertakes the polarization of the first and the second actuator in a manner in which the change in length generated by the polarization in the first actuator is compensated for by the change in length generated by the polarization in the second actuator.

In a further preferred embodiment at least one retaining element of the pretensioning device which is used for retaining the piezoelectric actuator is mounted to allow movement and its position is changed by the control unit in the corresponding manner in order to compensate for changes in length of the piezoelectric actuators occurring during the start phase.

The invention is explained in greater detail below with reference to the figures. The figures show

Fig. 1 a schematic diagram of the structure of a piezoelectric actuator,

Fig. 2 a device for polarizing a piezoelectric actuator,

Fig. 3 characteristic curves of a first polarization process, and

Fig. 4 characteristic curves of a second polarization process.

Fig. 1 shows a schematic diagram of the structure of a first piezoelectric actuator 1 which consists of a plurality of piezoelectric layers 11. The piezoelectric layers 11 are

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arranged one above the other in the form of a stack, with a piezoelectric layer 11 being delimited by two flat electrodes 12 in each case. This means that an electrode 12 is arranged between two piezoelectric layers 11 in each case. The stack the layers is delimited at its lower end by a cover plate 16 and at its upper end by a second cover plate 17. The two cover plates 16, 17 are tensioned between a sleeve-shaped tubular spring 18, which is only shown schematically in Fig 1. The tubular spring 18 pretensions the first and the second cover plate 16, 17 in the direction of the layer stack of piezoelectric layers 12. Depending on the desired embodiment the tubular spring 18 can also be dispensed with.

The electrodes 12 are essentially embodied in accordance with the flat shape of the piezoelectric layers 12. The electrodes 12 are connected alternately to a first or a second conductor 14, 15. The first and the second conductor 14, 15 are arranged on opposite edge areas of the layer stack. So that not every electrode 12 is contacted with each first and second conductor 14 and 15, corresponding cutouts 13 are provided so that an electrode 12 is only contacted electrically conductively with a first or second conductor 14, 15. The cutouts are located adjacent to the first or the second conductor at 14, 15 in the area of the electrodes 12. In this way it is ensured that a piezoelectric layer 11 is arranged between two electrodes 12 which are connected electrically conductively to the first or to the second conductor 14, 15. If a voltage is now applied to the first and the second conductor 14, 15, the voltage is applied to two electrodes 12 of a piezoelectric layer 11 in each case. The layer stack with piezoelectric layers 11 thus

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represents a series circuit of a plurality of piezoelectric layers. The layer stack represents a monolithically embodied multilayer piezoactuator.

The first actuator 1 can be used as a valve drive for example and has an operating time and which can exceed 10^9 operating cycles. The electrodes 12 are preferably embodied as metal electrodes. The first and the second conductor 14, 15 are initially used for a polarization of the piezoelectric layers 12 and subsequently for operation of the actuator 1. To enable operating strokes of 5 to 60 μm to be achieved would the first actuator, a stack height of 5 to 40 mm is required, which corresponds to up to 1000 piezoelectric layers 11.

After the construction of the layer stack the sintered ceramic particles of the piezoelectric layers 11 have spontaneous polarization areas with different directions of polarization. The spontaneous polarization is associated with a deformation of the crystal grid. Internal tensions which arise can to some extent be reduced only by the formation of domains. After the spontaneous polarization, the dipole moments of the individual domains are aligned so that they compensate for each other as a result of the statistically distributed directions of polarization.

For the provision of usable operating strokes it is required to align the directions of polarization of the dipole moments of the individual domains in one direction. The alignment of the dipole moments is achieved by applying an electrical polarization field to the piezoelectric layers 11, whereby a polarization of the dipole moments of the domains in parallel

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to the longitudinal axis of the first actuator 1 occurs, since the electrodes 12 are arranged at right angles to the longitudinal axis of the actuator 1. In addition the layer stack experiences a remanent length change in the longitudinal axis of the stack. To improve the polarization behavior the layer stack consisting of the piezoelectric layers 11 is subjected to the polarization field and polarized under a defined compressive stress. The polarization field is created by applying a polarization voltage to the first and the second conductor 14, 15. Optionally a polarization temperature of 20 to 150°C can be set. Typically electrical polarization fields are used which have a strength of 2 to 2.5 kV/mm. The polarization field and the compressive stress are maintained throughout the polarization period. For typical polarization processes polarization times in the range of a few minutes are normal.

Trials have shown that piezoelectric actuators 1 with especially good properties can be produced by the polarization of the piezoelectric layers 11 of the piezoelectric actuator 1 being created with variable polarization fields. In this case a number of voltage pulses in sequence in the form of characteristic curves with varying amplitudes are applied during the polarization process. During a polarization process the varying voltage causes a varying electrical polarization field to be applied to the piezoelectric layers 11. The amplitude of the characteristic curves of the voltages can have a sine wave shape, a square wave shape also other and voltage curve shapes with changing amplitudes. With this method however a problem arises in keeping the compressive

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stress exerted on the layer stack within defined limits. This is difficult since in the polarization process of the piezoelectric actuator its length changes in accordance with the changing voltage.

The compressive stress operating on the piezoelectric actuator 1 should lie within a defined range, not exceed a certain maximum value and not fall lower than a certain minimum value in order not to adversely affect the quality of the polarized actuator 1. The change in length of the piezoelectric actuator 1 requires in the prior art that the spacing of the retaining elements between which the piezoelectric actuator 1 is tensioned in the polarization process is varied so that the compressive stress operating on the piezoelectric actuator 1 remains within the desired tensioning range. As the frequency of the voltage which is applied during the polarization process to the piezoelectric layers 11 increases, the change in distance between the two retaining elements of the tensioning device becomes ever more difficult to maintain. As a result of the kinetic energy of the retaining elements a precise setting of the pretensioning force during the polarization process can no longer be maintained at high frequencies of the polarization voltages.

The invention proposes an improved polarization method and an improved device for executing the polarization method which will be explained in greater detail with reference to Fig. 2. Depending on the selected design, the first actuator 1 is polarized before or after it is incorporated into the tubular spring 18.

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Fig. 2 shows a schematic diagram of a pretensioning holder 4, which features two retaining elements 5, 6 which apply a selectable pretensioning force to the first and the second piezoelectric actuator 1, 2 during the polarization process. The retaining elements 5, 6 are effectively connected to each other via a housing 7. In the embodiment shown the first retaining element 5 is fixed to the housing 7. The second retaining element 6 is mounted on a housing 7 via a mechanical arrangement 8 which allows movement. In the embodiment shown, the mechanical arrangement 8 is embodied as a motor with a worm drive. Controlling the motor 8 in the corresponding manner enables the position of the second retaining element 6 to be moved along the longitudinal direction of the housing 7. This alters the length L between the two retaining elements 5, 6.

The motor 8 is connected via control leads to a control unit 9. The control unit 9 is connected via first control leads 10 to the first actuator 1. The first two control leads 10 are connected to the first or the second conductor 14, 15 of the first actuator 1. The first actuator 1 is arranged in the longitudinal direction in parallel to the housing 7 and rests with the second cover plate 17 on the first retaining element 5. In a preferred embodiment a pressure sensor 19 is arranged between the first retaining element 5 and the second cover plate 17 of the first actuator 1. The pressure sensor 19 is connected via a signal line 20 to the control unit 9. The pressure sensor 19 records the pretensioning force which is exerted by the pretensioning holder 4 on the first and second actuator 1, 2.

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In the exemplary embodiment shown the second actuator 2 is arranged between the first actuator 1 and the second retaining element 6. The second actuator 2 is preferably embodied identically to the first actuator 1. Preferably a second length 12 of the second actuator 2 is equal to a first length 11 of the first actuator 1. The second actuator 2 is connected via two second control lines 21 to the control unit 9. One of the second control lines 21 is connected to the first conductor 14 and the other second control line 21 is connected to the second conductor 15.

To execute a polarization process the control unit 9 applies a defined pretensioning force in the longitudinal direction to the first and the second actuator 1, 2 such that the second retaining element 6 is moved via the motor 8 in the corresponding manner in the direction towards the first retaining element 5. Depending on whether the pressure sensor 19 is provided or not, either experimentally determined movement paths of the second retaining element 6 are used to control the motor 8 or the control unit 9 records during the movement of the second retaining element 6 via the pressure sensor 19 the pretensioning force operating on the first and the second actuator and moves the second retaining element 6 until such time as the desired pretensioning force is present at the first and the second actuator 1, 2.

Figure 3 shows schematic characteristic curves of a polarization process of the two actuators with a start phase. In Figure 3a the polarization voltages P1, P2 are plotted over the time t. In Figure 3b the length changes W1, W2 of the first and of the second actuator 1, 2 are plotted over the

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time t . In Figure 3c the sum of the length changes of the first and the second actuator 1.2 are plotted over the time t . The start phase extends from the time zero t_0 to the start time T_A of the second phase.

In a preferred embodiment, in parallel to the setting of the pretensioning force a variable first polarization voltage, of which the amplitude varies by a rising average value, is applied to the first actuator 1. In addition a second changing polarization voltage is applied to the second actuator, during a start phase of which the amplitude varies by an increasing second average value. The first and the second polarization voltage are tailored to each other in such a way that the sum of the first and the second polarization voltage constantly increases to a defined value. The first and the second polarization voltage can have different voltage curves. In Figure 3a the first and the second polarization voltage are represented in the form of sine wave curves which have a phase offset to each other of 90° .

As a result of the increase of the average value of the first polarization voltage P_1 the first length L_1 of the first actuator 1 changes accordingly by a first length change W_1 , as is shown in Figure 3b. Because of the increase of the average value of the second polarization voltage P_2 during the start phase the second length L_2 of the second actuator 2 increases accordingly by a second length change W_2 , as shown in Figure 3b. This means that, as a consequence the pretensioning force acting on the first and the second actuator 1, 2 increases independent of the relative position of the first and the second retaining element 5, 6.

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At the end of the start phase after the start time T_A of the second phase the first and the second polarization voltage P_1 , P_2 have reached a maximum average value around which the first and the second polarization voltage P_1 , P_2 vary. The first and the second polarization voltage P_1 , P_2 are embodied after the start phase so that the sum of the first and the second polarization voltage P_1 , P_2 is essentially constant over time. Since the sum of the polarization voltages is essentially constant over time, the sum of the length changes (W_1+W_2) of the first and of the second actuator is also essentially constant over time, as shown in Figure 3c.

The desired pretensioning force is set by the control unit 9 on application of a first polarization voltage P_1 to the first actuator 1 and on application of a second polarization voltage P_2 to the second actuator 2 by setting the distance of the retaining elements 5, 6 to a desired value during a start phase.

Since the sum of the changes in length (W_1+W_2) of the two actuators 1, 2 essentially remains constant after the start phase it is not necessary, despite the first and second polarization voltages P_1 , P_2 varying around the relevant average value, to change the distances between the first and in the second retaining element to keep the maximum pretensioning of the first and of the second actuator within a defined range of values.

This means that the first and the second polarization voltages can exhibit high frequencies with which the first and the second polarization voltage vary around the relevant average

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family without an adjustment of the distance of the first and second retaining element being necessary. The high frequencies which this makes possible are advantageous for the polarization of the first and/or the second actuator.

Figure 4 shows characteristic curves of a further embodiment of the method after the start phase in the second phase after the start time T_A in which saw-tooth type curves are selected as curves for the first and the second polarization voltage P_1 , P_2 . In Figure 4a the curves of the first and the second polarization voltage P_1 , P_2 are shown which are applied to the first and the second actuator 1, 2. After the start phase the first polarization voltage P_1 is present at the start time T_A with a maximum value at the first actuator 1. The second polarization voltage P_2 has the value 0.

The first polarization voltage P_1 , which is fed to the first actuator 1, and the second polarization voltage P_2 , are embodied such that the sum of the first and the second polarization voltage remains essentially constant over time. To this end the curve shapes are identical, but are displaced over time so that the sum (P_1+P_2) of the first and the second polarization voltage is essentially constant.

The sum (P_1+P_2) of the polarization voltages P_1 , P_2 is shown in Figure 4b. As a result of the constant sum of the polarization voltages the total length L of the series arrangement of the first and of the second actuator 1, 2 which is produced from the first length l_1 and the second length l_2 of the first or the second actuator 1, 2, is essentially also constant. The overall length L is shown in Figure 4c. Slight

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variations in the overall length L can be accepted, so long as the pretensioning force operating on the first and the second actuator does not go beyond a defined range.

At the start point TA of the second phase the first and the second actuator 1, 2 have an initial length. The first and the second retaining element 5, 6 are spaced from each other by a distance defined by the control unit 9. In addition a desired pretensioning force FG is exerted on the actuators 1, 2 via the retaining elements 5, 6. A maximum polarization voltage U_{max} is present at the first actuator 1 a start time TA . No second polarization voltage $P2$ with the value 0 volt is present at the second actuator 2 at point in time TA . The sum of the first and the second polarization voltages $P1$, $P2$ corresponds at the start time to the maximum voltage value U_{max} . The start point already represents the first method step after the start phase. Subsequently in a second step, the second polarization voltage $P2$ can be raised to a higher value. The higher and the lower value of the polarization voltages $P1$, $P2$ depend on the desired polarization process.

In the exemplary embodiment shown, the first polarization voltage $P1$ is lowered in a linear manner from the maximum voltage value U_{max} to the value 0 volt at the first point in time $T1$. Simultaneously the second polarization voltage $P2$ is increased from the value 0 volt linearly up to the first point in time $T1$ to the maximum voltage value U_{max} . During the first method step, i.e. between the start point TA and the first time $T1$, the sum of the polarization voltage $P1 + P2$ essentially corresponds to the maximum voltage value U_{max} . Depending on embodiment, the sum of the polarization voltages

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can however also vary slightly, as shown in the diagram in Fig. 4b.

Ideally the total length L should correspond during of the first polarization step, i.e. between the start time T_A and the first time T_1 , essentially to the start value. However, both because of inaccuracies during activation and also through deviations of the material properties of the first and second actuator 1, 2, slight changes or variations of the total length during the first polarization step can occur. The pretensioning force which is shown in Figure 4d should remain essentially constant during the first method step. Because of inaccuracies in the activation or different material properties of the first and the second actuator 1, 2, small deviations from the start value of the pretensioning force F_G and also occur.

Subsequently, in a third method step between the first and the second point in time T_1 , T_2 the first and the second polarization voltage P_1 , P_2 are kept constant.

Subsequently in a fourth method step after the second point in time T_2 the second polarization voltage P_2 is reduced in a linear fashion until the third point in time T_3 to the value 0 volt. Simultaneously the first polarization voltage P_1 is increased, starting from the second point in time T_2 , starting from the value of 0 volt, up to the maximum voltage value U_{max} until the third point in time T_3 . The symmetrical change of the polarization voltages, as can be seen from Fig. 4a, is repeated for a defined period of time. The defined period of time is determined empirically, with the period of time being

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selected to be long enough to achieve a desired polarization state of the first and/or the second actuator 1, 2.

Depending on the application, the time segments in which the first and the second polarization voltage P1, P2 are kept constant can be reduced or even omitted completely. In addition the changes of the first and of the second polarization voltage P1, P2, instead of exhibiting a linear change, can also exhibit other change behaviors over the time such as for example graduated changes or exponential changes or changes of any other type.

Since during the start phase of the polarization process a change in the total length L of the first and the second actuator 1, 2 occurs, in an advantageous embodiment the distance between the first and the second retaining element 5, 6 is increased during the start phase. The distance thus increases from an initial value up to an end value at the end of the start phase. Thus the total length L also increases during the start phase from a start value up to an end value at the end of the start phase.

The pretensioning force which operates on the first and the second actuator 1, 2 should essentially be kept within a defined range of values. This means that variations around the start value FG of the pretensioning force are allowed. At the end of the polarization process both polarization voltages P1, P2 will be reduced to the value 0 and the pretensioning force will subsequently also be reduced to the value 0.

The frequency of the polarization voltages with which the first and the second actuator are supplied depends on the

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actuators 1, 2 used and can lie within the range of a few 100 Hertz.

The invention has been explained using an example in which a second actuator 2, which is essentially embodied identically to the first actuator, is arranged in series with the first actuator 1. This offers the advantage that the first and the second actuator 1, 2 essentially exhibit the same length change behavior as a function of the polarization voltage applied. This means that both the change over time of the length and also the maximum deflection produced at maximum voltage U_{\max} of the first and the second actuator are identical. Thus, for the polarization of the first and the second actuator, the same curve shapes can essentially be used for the first and the second polarization voltage P_1 , P_2 which however are displaced in time relative to one another. Through this method two non-polarized actuators can be used in one polarization process in each case so that two actuators are polarized at the same time in one polarization process.

In a further embodiment different piezoelectric actuators can also be connected in series. This however requires a greater effort for polarization since different profiles must be used for the polarization voltages of the two actuators in order to keep the total length L which is made up of the sum of the lengths of two actuators essentially constant during the polarization. With two actuators which have different piezoelectric properties the corresponding profiles for the polarization voltages are also embodied differently. In order to also achieve a restriction of the pretensioning force F in the desired area for piezoelectric actuators with different

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piezoelectric properties, the polarization voltages P1, P2 can also be regulated via the recording of the pretensioning force by the pressure sensor 19. In this case the control unit 9 uses the pressure sensor 19 to monitor the compressive stress present at the first and the second actuator and regulates the polarization voltages P1, P2 of the two actuators 1, 2 such that the pretensioning force F stays within the desired range and, despite this, the first and the second actuator are supplied with a pulsed polarization voltage and a remanent polarization of the first and the second actuator is achieved. However curve shapes determined empirically for the two polarization voltages can also be used.

In a further preferred embodiment, instead of the second actuator 2, any other compensation element can also be used with which the length change of the first actuator 1 can essentially be compensated for during the polarization process. The compensation element can for example be constructed from a number of piezoelectric actuators which are activated in the appropriate manner by the control unit 9. However a compensation element could also be used which essentially operates with spring forces and is constructed as a passive compensation element and limits the pretensioning force to a maximum value.

Fig. 5 shows an advantageous circuit arrangement for supplying the first and the second piezoelectric actuator 1, 2 with corresponding polarization voltages. In this exemplary embodiment the first conductor 14 of the first actuator 1 is connected to a first voltage U1 and the second conductor 15 of the second actuator 2 to a third voltage U3. The first voltage

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U1 and the third voltage U3 are each constant and exhibit a potential difference. In the selected exemplary embodiment the first and the third voltage U1, U3 are positive, with the first Voltage U1 having a minimum voltage value Umin and the third voltage U3 a maximum voltage value Umax. The second conductor 15 or the first actuator and the first conductor or the second actuator 2 are connected to each other and are supplied by the control unit 9 with an AC voltage U2 which fluctuates between the maximum voltage value Umax and the minimum voltage value Umin. As a result of the advantageous circuit arrangement it is sufficient to supply the first and the second actuator with only one AC voltage and two constant, but different voltages. In this way a simple and cost-effective voltage supply during the polarization process is possible.